

Measuring Contact Stress inside Weapon Systems

Tiny, flexible sensors take measurements never before possible.

OVER the past decade, microfabrication techniques have revolutionized numerous technologies. Virtually every industry from biomedicine to transportation has replaced traditional electrical and mechanical instruments with increasingly smaller devices that exhibit superior performance and longer lifetimes. Among the devices that push the limits of miniaturization are microelectromechanical systems (MEMS) fabricated from silicon and other materials to sense and react to environmental changes.

MEMS' small dimensions, material properties, low power consumption, and mass manufacturability offer new sensing opportunities, such as measuring loads where two objects are in contact. Contact measurements are important for numerous

applications, from gaskets, seals, brakes, and air bags in the automotive industry to artificial limbs, knee orthopedics, and hip replacements in medicine. Some of the Laboratory's work in stockpile stewardship would benefit from the ability to accurately characterize loads in a weapon over its long lifetime using onboard diagnostics. MEMS offer an approach for introducing stress sensors for the first time into these applications and many others.

Stress sensors measure contact loads by converting applied pressure, or contact stress, between objects to a recorded change in electrical resistance. To measure loads at an interface, such as in the human knee, a sensor must be extremely thin and flexible so the sensor's presence doesn't alter the stress it is measuring. Because of this size requirement, the application of existing sensing technologies to many research efforts and commercial products has been limited. In weapons diagnostics, meeting the longevity, accuracy, and geometry constraints of contact stress measurements poses additional challenges. The demands of monitoring weapons in the stockpile require unusually thin and flexible devices.

Measuring Stress in Weapons

The Department of Energy's (DOE's) National Nuclear Security Administration (NNSA) is responsible for ensuring the safety and reliability of the nation's nuclear weapons stockpile through its Stockpile Stewardship Program. To audit the health of the stockpile, DOE established a program that includes using representative test units for each stockpile weapon, called Joint Test Assemblies (JTAs), to obtain diagnostic measurements. Tests involving JTAs are

conducted annually by Lawrence Livermore, Los Alamos, and Sandia national laboratories.

The annual assessment includes flight and ground tests of the units and, at times, the dismantlement of randomly selected weapons for inspection. Although these activities are effective at determining information about physical performance characteristics, they do not reveal valuable data on the mechanical history of a weapon.

Mechanical engineer Jack Kotovsky says, "It's difficult, if not impossible, to predict load distribution. Direct measurements using stress sensors are the only way to accurately determine the contact mechanics inside a complex assembly." Commercial stress sensors that can meet the demands of weapons diagnostics and enable researchers to obtain these valuable data do not exist.

Through funding from NNSA, Kotovsky leads a team that has designed the first MEMS contact stress sensor to meet the demanding requirements. The single-sensor silicon device is the only contact stress sensor that can repeatedly measure changing loads perpendicular to a surface within a weapon system. The device is 4 millimeters square and 50 micrometers thick (for comparison, a human hair is 100 micrometers thick) and is embedded in a polyimide film package. A completely packaged device measures 100 micrometers thick.

The effort is a result of a collaboration formed in 1999 between Livermore's Defense and Nuclear Technologies and Engineering directorates to develop a new family of sensors that could be used for integrated diagnostics in JTAs. The design for Livermore's stress sensor originated from Kotovsky's interest in developing a



One stress sensor measures just 4 millimeters square and 50 micrometers thick.

sensor used as an orthopedic tool for knee-joint contact studies. When he was a graduate student at the University of California at Davis, Kotovsky contacted Livermore's Center for Meso, Micro, and Nanotechnologies, because it had the equipment he needed to complete the research for his dissertation. The center's MEMS fabrication facility is used to develop smaller, more reliable device technologies for the Laboratory's national security missions.

Assembling Microsensor Parts

Fabricating stress sensors is a time-intensive process. Holly Petersen, a key member of Kotovsky's team and one of

the center's technicians, begins the process with a 102-millimeter-diameter, 500-micrometer-thick wafer of silicon that is bonded to a 15-micrometer-thick wafer. A 200-nanometer-thick silicon oxide layer acts as a glue to bond them. Silicon is often chosen as the substrate material for MEMS sensors because of its consistent response to deformation under changing pressure. When a certain amount of pressure is exerted on a sensor's silicon diaphragm, it will deflect and spring back, repeatedly, to its original position when the pressure is removed. (See the **box** on p. 7.)

Once the silicon layers are prepared, a thin layer of photosensitive material, called photoresist, is coated on the silicon wafer

and baked. Ultraviolet light rays are then sent through a series of seven computer-generated masks. Each mask is dedicated to a layer on which a pattern is transferred by a process called photolithography.

In one of the processing steps, a silicon wafer is placed in a chamber that implants boron ions in specified areas, creating conductive traces. Adding boron allows the silicon to respond with significant changes in electrical conductivity as atoms in the crystal lattice stretch and spring back with applied pressure. One of the masks defines a pattern for a diaphragm on the silicon that will serve to measure contact stress applied to the device. Applied loads will cause the diaphragm to deflect, thereby causing stress on the silicon. The boron-doped traces register the amount of change in the resistance. A photolithographic step is also used to define the copper traces on the polyimide film package that will connect the embedded MEMS devices to external electronics.

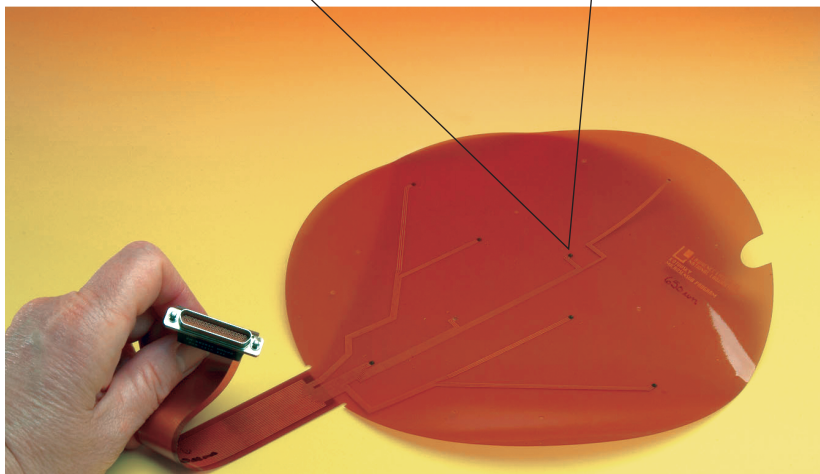
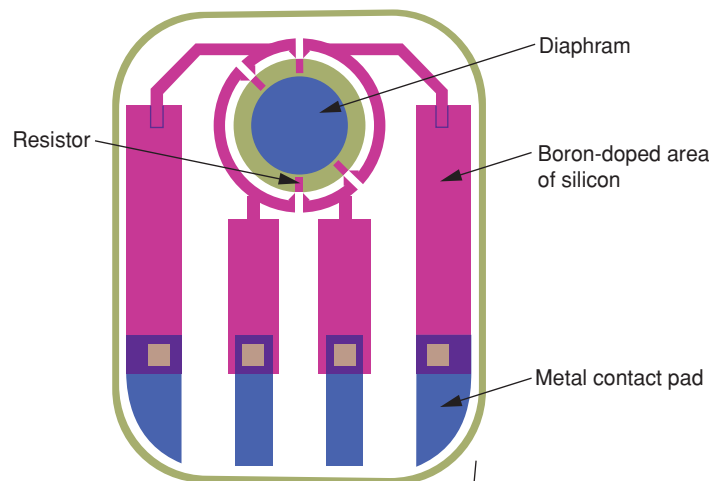
Silicon's resistivity depends on both temperature and pressure. Temperature changes in the surrounding environment cause silicon to register resistance change in the same way as if pressure were applied. To compensate for this effect and ensure that only contact load is being measured, Kotovsky designed the device with four resistive boron traces. All four respond to temperature, but only two respond to pressure. The difference between the two sets of measurements isolates the response due to load.

The Livermore design is the first in which the circuitry is embedded within layers of polyimide using generic, flexible circuit processing. "Flexible circuit technology is a good packaging choice for MEMS sensors because it's strong, mechanically and thermally stable, and inexpensive," says Kotovsky.

Designing Sensor Arrays

The MEMS sensor was initially designed to perform repeatedly under loads at one location on a surface. However, in many

(top) Four boron-doped resistors register the change in resistance as pressure is exerted on the stress sensor's diaphragm. (bottom) A polyimide film encases microelectromechanical sensors in the sensor package. The copper traces are routed to external electronics.



instances, measurements are needed for loads distributed over an area. Expanding the single sensor design to an array of sensors has been difficult, in part because silicon is brittle and does not conform to complex curvatures.

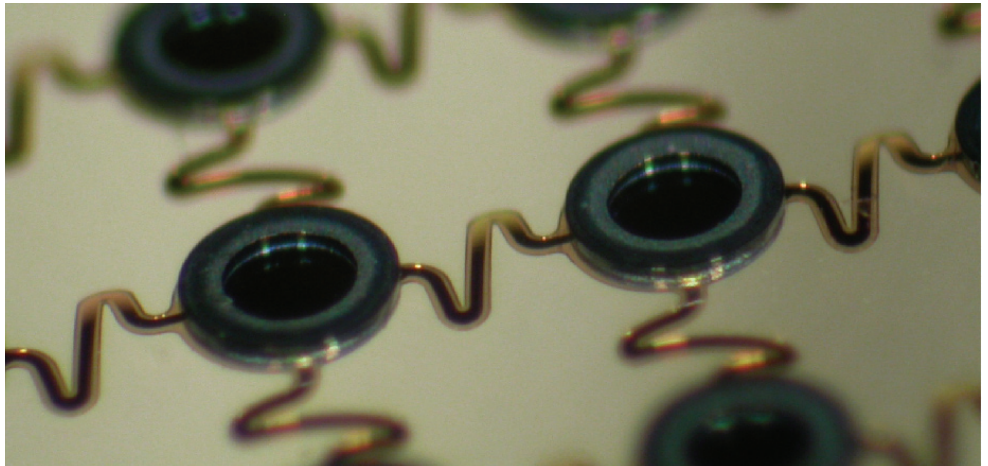
Kotovskiy has developed designs for large arrays of contact stress sensors that can bend, flex, and stretch to conform to surfaces of any curvature. "The sensor arrays are interconnected in such a way that they behave similar to a fabric, allowing complex-curvature conformity," says Kotovskiy. The Livermore team has demonstrated designs for continuous silicon arrays of more than 1,000 sensors that bend and flex. A unique feature of their array designs is the use of independent "islands" of silicon that each contain a sensor and are interconnected by freestanding or polymer-backed conductive springs. "Arrays of independent silicon devices allow enormous flexibility, which is useful for a variety of applications," says Kotovskiy.

To assist with the fabrication challenges for the array, Kotovskiy enlisted Adam Mednick, a graduate student from California Polytechnic State University in San Luis

Obispo. In one Livermore array design, serpentine gold wires interconnect islands of silicon. Mednick found a fabrication solution in which each of the gold wires is encased in polyimide to provide mechanical and electrical protection to the wires.

Increasing the number of sensors for an array also meant finding a method to address the effect of temperature. Duplicating the approach for the single sensor would be

impractical for an array with hundreds of sensors. As an alternative, Kotovskiy designed an array in which the sensors are interrogated in a grid. A sensor in the corner of the grid does not have a stress-sensing diaphragm and only registers temperature. Resistance changes due to temperature can be determined by comparing results from a resistor with a diaphragm and one without a diaphragm.



Freestanding conductive gold wires connect a flexible, springlike array of stress sensors.

Fabricating Microsensors and Actuators

Research on microelectromechanical systems (MEMS) sensors dates from the late 1960s. Most MEMS devices can be classified as either sensors or actuators. Sensors convert a form of energy produced by a phenomenon being measured to a signal that represents a change. For example, the mercury in a thermometer will expand as a result of a rise in temperature. Actuators move or manipulate phenomena based on energetic input. For example, when electricity is applied to a motor, the motor will spin or activate.

MEMS sensors and actuators are fabricated using techniques similar to those used by the electronics industry. Structures are assembled in layers of materials, typically semiconductors, dielectrics, metals, and polymers. The microfabrication processes commonly used are surface micromachining and bulk micromachining. These processes include photolithography, chemical vapor deposition, ion implantation, chemical etching, metal evaporation, sputtering, and plasma etching to produce mechanical and electronic structures. The most common method used to transfer design geometries is photolithography, or patterning a design into

photosensitive materials. In photolithography, a photosensitive but chemically resistant (photoresist) masking material is applied onto the substrate material in a particular pattern. The structural layer is then etched, implanted, or metallized, according to the photoresist pattern, and the photoresist is removed. This process is repeated until all the desired layers have been patterned.

In some applications, microsensors are embedded into structures and have no physical connection to outside the device. Therefore, the development of MEMS requires micropower supplies to be integrated into the microsensor system. A power supply on the same scale as the MEMS device permits a stand-alone integrated system that can be fully functional within its environment.

Miniaturized devices can provide numerous performance advantages, including simple installation and maintenance and lower power consumption. The most important quality for sensors is that they are compatible with the environment in which they operate, so they can provide accurate measurements.

The stress sensors will provide researchers involved in the JTAs with the ability to obtain important data on weapons in the stockpile. "These sensors will enable us to take measurements in a weapon that were never before possible. We can take measurements in situ and transmit the collected data without dismantling the weapon," says Tony Lavietes, who leads Livermore's Microsensors Program. Sandia is currently preparing to manufacture the single-sensor device that will be used in JTAs. NNSA's Kansas City Plant is manufacturing the polyimide package. The design for both the single sensor and the array are available for licensing.

Optical Sensor Technologies

Livermore researchers are also studying possible sensors that could replace electronic systems, which are not compatible with

some components of weapon systems. One possibility is the use of optical technologies. The data gleaned from nonnuclear JTAs have shown researchers there would be value in developing enhanced diagnostics for the explosives package in a nuclear weapon. Sensors used in diagnostic systems for the nuclear explosives package are not intended to be powered electrically, because of the remote possibility of contact with energetic materials such as high explosives. Optical sensors are intrinsically safe and are ideal for use in harsh environments that include radioactive and energetic materials.

Engineer Mike Pocha, also with the Center for Meso, Micro, and Nanotechnologies, led a team that developed a miniaturized signal-processing system for a Fabry-Perot optical sensor. This sensor is an interferometer in which changes in the phase of light are measured to determine the behavior of the property being studied. A collimated light-emitting diode broadband source is sent through an optical fiber to an optical sensor. The object of interest interacts with the sensor, changing the phase of the reflected light. The reflected light is transmitted back along the same pathway. The processor measures the phase modulation and sends the processed signal to an external instrument.

One limitation of commercial optical systems is that the signal processors are too

large to be used in many applications, including weapons diagnostics. The Livermore-designed signal processor is enclosed in a 2- by 8-centimeter package, and the team is hoping to shrink it further to the size of a sugar cube. Still, the current design is several times smaller than commercial processors. Its small size would allow it to be connected to an optical fiber sensor for use in applications where minimal sensor size is critical. Pocha says, "Commercial optical fiber sensors have been available for about 10 years. They can measure a limited set of parameters such as temperature, pressure, and strain. However, for many Laboratory missions, we are developing optical sensors that measure additional properties such as force, gas composition, and acceleration."

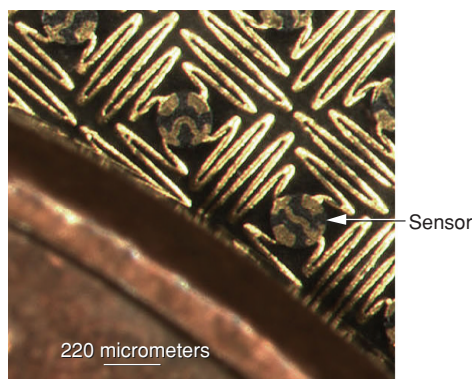
Reliability over the Long Term

Researchers in the Microsensors Program have designed several optical sensors that are compatible with Pocha's processing system, including an optical gap gauge and force probe designed by Kotovsky and Billy Wood. Another member of the team, Steve Swierkowski (now retired), has developed an optical accelerometer, which is available for licensing.

Single electronic MEMS sensors, sensor arrays, and optical sensors will all benefit future JTAs. Lavietes says, "The idea is to provide a portfolio of sensors to conduct diagnostics on weapon performance. Those conducting the tests could then pick what type of sensor is best suited for the job. For a replacement weapon that might be developed, these onboard, integrated diagnostics would be a valuable component. Today, in order to perform a comprehensive assessment, researchers must disassemble a sampling of weapons over time. In addition to this being extremely expensive, the costs in transporting and securing a weapon are also significant, especially when it's a nuclear weapon."

Another cost savings from integrating sensors would be a reduction in the number

A flexible sensor array is designed to bend and stretch over any curvature.



Serpentine gold wires, each encased in polyimide, connect "islands" of silicon stress sensors.

of weapons needed. Traditionally, the number manufactured includes some that will be pulled from the stockpile over the weapon system's lifetime and disassembled for testing. Integrated diagnostic systems could provide the information currently obtained from disassembly activities, and the overproduction to accommodate these surveillance requirements could be greatly reduced or eliminated.

The primary requirement for sensors is reliability. "The device is going to be in the weapon for 20 to 50 years," says Laviates. Reliability and inherent safety over a long lifetime are critical requirements for many Laboratory efforts. Anantha Krishnan, director for research and development at the Center for Meso, Micro, and Nanotechnologies, says, "A big difference between the technologies developed at Livermore and those of commercial industries is that the commercial sector plans on a technology being obsolete in as few as 2 years. In contrast, we often need technologies that last a long time. Developers of electronic games, who are driving new technology today, don't have to plan for a product to be safe and reliable for 30 years. Our goal is to use the best technology possible and still provide the longevity and safety we need." The materials in the Livermore stress sensor—silicon, copper, and polyimide—are chemically stable and have characteristically long lifetimes.

Advancing Biomechanics Research

Kotovskiy plans to design a three-axis sensor, one that can measure normal loads and shear loads, or forces from two additional sides. He also hopes to continue work on stress sensors for orthopedics. "About 10 percent of annual visits to orthopedic surgeons are related to knee injuries, and about 40 percent of those visits are directly related to meniscal injuries," says Kotovskiy.

Originally assumed to be nonfunctional, the meniscus plays an important role in transmitting force between the femur and



Jack Kotovskiy characterizes the processing of a MEMS sensor array on a scanning electron microscope.

the tibia. In the past, orthopedic surgeons removed the entire meniscus when it was damaged. It was later discovered that removing the entire meniscus causes progressive degeneration of the cartilage in the knee. Eventually, this condition leads to osteoarthritis because of increased contact pressures and the alteration of load distribution on the joint. In recent years, efforts have been made to preserve, repair, and replace the damaged meniscus, but significant work remains to improve these procedures. Eventually, the Livermore-designed sensor could provide biomechanists with the precise measurements they need to improve surgeries.

Some studies have suggested that a meniscus from a cadaver could be used to replace a damaged meniscus. If so, the stress sensor could help orthopedic surgeons determine the shape and size of the meniscus and the best method to transplant one into a patient. "However," says Kotovskiy, "until transplanting a meniscus is shown to be effective at preserving healthy cartilage stress distribution in the knee, surgeons will not be inclined to adopt this difficult operation."

Livermore's Center for Meso, Micro, and Nanotechnologies has accomplished critical milestones in novel techniques for photolithography, wafer handling, silicon

etching, and sensor design. "The Holy Grail," says Krishnan, "would be to have an integrated platform of sensor, processor, and actuator operating in an autonomous mode. In the last several years, tremendous progress has been made in processing information from sensors. Linking this information to the decision-making processes that exist in an architecture such as that of the human brain so that actuators can respond with the appropriate solution would truly be remarkable."

—Gabriele Rennie

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